The Plasma Sheet Source Groove

T.E. Moore[1], B. L. Giles[1], D. C. Delcourt[2], and M.-C.Fok[3]

[1] NASA Goddard Space Flight Center, Greenbelt, MD, USA
[2] Centre d'Études Terrestre et Planétaire, Saint Maur, France
[3] Universities Space Research Association, Greenbelt, MD, USA.

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Abstract

A test particle study of the ionospheric source of plasma in the Earth's plasma sheet has been performed, in an effort to understand an apparent inconsistency between the results of forward and backward (in time) test particle calculations. Most if not all forward calculations of polar wind ion outflows result in energetic plasma sheet ion populations; yet most if not all backward trajectory calculations from typical plasma sheet ion populations lead elsewhere than to low energy polar cap outflows. Using a trajectory discovered through forward calculation to connect these two regions, we found that the trajectory was only accurately reversible within an extremely narrow range of energy, pitch angle and gyrophase angle in the plasma sheet, referred to herein as "the source groove". This implies that ionospheric plasma tends to appear in the plasma sheet within narrow regions of velocity space, but is effectively diffused by fluctuations to form the observed more isotropic plasma sheet populations. The implications for backtracking test particle studies are not discussed, and it is concluded that test particle backtracking from highly chaotic regions is impractical and should be supported by forward modeling of plasma flows up to the boundaries of such regions.

Introduction

Recent computing advances have encouraged increasingly routine exploration of the full equations of motion of particles in specified but realistic three-dimensional magnetic and electric fields [Delcourt 1997, 1994, 1990; Joyce et al.,1995; Moore and Delcourt, 1995; Abdalla et al., 1993, 1997]. Some workers have begun pushing particles using the full equations of motion in self-consistent fields derived from MHD simulations, a further step forward. Others are beginning to perform hybrid simulations of fully 3D systems using kinetic ions and fluid electrons [Nishikawa, 1998]. Nevertheless, we have found that there is still significant insight to be gained from single particle motions in specified fields, particularly with regard to understanding the sources and flow paths of plasmas within an ionosphere-magnetosphere system [e.g. Delcourt et al., 1995; Fok et al., 1999, Giles et al., 1999].

In the past few years, test particle simulations have grown increasingly ambitious in terms of the number of particles being tracked. Yet as much as the number of particles tracked in such simulations has increased, it has not been possible to treat a realistic spatial distribution of sources, at each point represented by a distribution of velocities. Were it possible to track enough particles, the trajectories would thread all of the space in the simulation with enough particles to construct a local velocity distribution at any point in the simulation space. This not yet being practical, a new approach has appeared [e.g., Ashour-Abdalla et al., 1999; Fok et al., 1999]. In this approach, here termed “test particle backtracking”, particles representative of the entire velocity distribution at a point in space are backtracked in time along reversible trajectories (neglecting diffusive field fluctuations), to points of origin that are dominated by specific plasma sources.

Using Liouville’s theorem, observations of the phase space densities at the destination region can be equated to those at the source regions that are connected to the destination by each trajectory. Ashour-Abdalla et al.[1999] inferred the source regions and their plasma characteristics from specific plasma sheet observations, while Fok et al. [1999] used typically observed source plasma characteristics to construct velocity distributions along a boundary in the inner plasma sheet. Either application of the backtracking approach can be accomplished using a much smaller number of trajectories than would be required to track all sources to all possible destination points.

When structures appear in the resulting distribution functions from kinetic modeling, it is accepted that these structures will be less sharp in observed distributions, owing to the diffusive effects of fluctuations present in real situations. Nevertheless, it is usually worthwhile to understand the plasma velocity features that derive from idealized versions of the fields, since there are many non-thermal features of space plasma velocity distributions that do seem to survive diffusive erosion. Space plasmas are thought to evolve toward a state of marginal stability, and the origin of the fluctuations that cause this evolution is usually thought to lie in the velocity space features that are created by smooth, non-fluctuating, "underlying" fields, creating the conditions for wave growth.

A number of papers [e.g., Cladis, 1986; Delcourt et al., 1995; Giles et al., 1999] have shown that out-flowing ionospheric ions originating from high latitudes convect anti-sunward as they flow outward along magnetic field lines, arriving at the plasma sheet in the more or less distant magnetotail, thereby providing a source of plasma sheet ions. The motions of particles in the fields that are typically used for these studies are perfectly reversible (apart from numerical diffusion in the computer codes), and can be run backward in time. Even though the motions in the neutral sheet give the appearance of "scattering" the particles, producing large changes in their pitch angles as well as their energies, the trajectories are not stochastic in nature, nor does entropy increase in an ensemble of particles travelling in continuous and steady fields that are usually used.

Yet, when plasma sheet particles are traced backward in time to their sources, as a means of specifying the velocity space distribution in the plasma sheet [Fok et al., 1999], it is exceedingly difficult to identify even a small subset of the trajectories that resemble the forward trajectories of ionospheric out-flowing ions. Even when 10's of thousands of trajectories were run backward from locations in the near-Earth plasma sheet, not a single one could be characterized as a polar wind like trajectory, originating at low energy from within the polar cap or dayside auroral zone. The more typical behavior of these trajectories, also found by Ashour-Abdalla et al. [1997, 1999], is that they travel backward in time, anti-sunward in the -Xgsm direction until they pop out of the neutral sheet at Xgsm ~ 40-60 Re. Then, instead of backing up Earthward as an ionospheric ion must, they trace to positions down the tail beyond the boundaries of the simulation space, originating in an earthward flowing component inferred to exist in the distant mantle [Ashour-Abdalla et al., 1999].

Thus we have an apparent discrepancy between forward and backward test particle results. We found this to be not only puzzling, but troubling in its implications. For example, one possible explanation of this kind of behavior might be that the trajectories are not reversible, even when motions are calculated in rather idealistic fields with no intentional stochastic character. Such an irreversibility would have to stem from errors in the particle code, since the equations are non-stochastic and rigorously reversible. This would call into question the accuracy and utility of test particle codes to trace the transport of plasma particles through the magnetosphere. We were suspicious that the strong gyro-phase bunching that results from chaotic neutral sheet acceleration [Delcourt et al., 1997], produces irreversible effects in the particle trajectories. In this paper we report on our investigation of this discrepancy, leading to the identification of non-adiabatic analogues of the familiar source-loss cone concept. First we describe our modeling technique. Then we display the results we have obtained, discussing their implications prior to summarizing conclusions that can be drawn.

Modelling Approach

The typical test particle backtracking study divides velocity space coordinates into a number of cells, each representing a set of "final" conditions used to initiate a particle trajectory backward in time to some source region. Even a coarse gridding into, say, 10 pitch angles, 10 energies, 10 gyrophases, and 10 spatial locations [as done by Fok et al., 1999], generates ~10^4 particles, but will only explore phase space angles to a resolution of 18-36 degrees. In fairness, it must be noted that such a procedure could easily fail to identify even a single trajectory that travels backward to the conjugate ionosphere from a location near geosynchronous orbit, where the source-loss cone is only 3 degrees in half angle. Advance knowledge of the source cone could allow the simulator to place cell centers at very small pitch angles, thereby producing at least a small sample of ionospheric source particles. However, random regular placement of the grid cells in the absence of such knowledge would likely result in missing the ionospheric source completely.

Fok et al. [1999] set up the grid of "final" conditions at L=12 R_E in the nightside plasma sheet, where rapid convection and a neutral sheet field geometry considerably complicate the particle trajectories. A simple source cone concept is inadequate to support the placement of grid cells so as to sample the true source regions in velocity space. Initiation of particles at very small pitch angles would indeed lead those particles to back up swiftly into the (nearly) conjugate ionospheric footpoint, apart from the rapid convective motions present. For some trajectories, connections to auroral locations may be found, and these trajectories might be populated with energetic ion fluxes. In fact such trajectories were the subject of some early trajectory studies by Delcourt [1988], concerned with the production of velocity dispersed ion streams (VDIS). However, these are not the trajectories we study here. Rather, we seek to identify those plasma sheet trajectories that back up in time through the plasma sheet and then sunward through the lobes to polar cap and dayside auroral sources. This allows us to resolve the paradox to which we referred above, and to trace a significant component of plasma sheet ions to the largest source of outflowing phase space density in the ionosphere [Yau et al., 1985].

The particle trajectory code we are using is that which has been used extensively in studies by Delcourt and co-workers [e.g., Delcourt et al., 1993]. For this study, we have specified the Tsyganenko T89 magnetic field with a purely dipolar Earth field and the magnetospheric current systems as specified by a fit to a variety of empirical data sets. This model has a neutral line only beyond its region of applicability (>70 R_E down tail), but we expect the results to be roughly scalable to the region earthward of a closer neutral line in other tail field models. We have specified the Volland-Stern model of the potential distributio in the ionosphere, which provides a bland and unstructured magnetospheric circulation that nevertheless captures its essential large-scale features. The electric field throughout the magnetosphere is calculated from ionospheric potential assuming that model field lines are equipotentials. Since each electric field computation involves three numerically-intensive field line tracings to the ionosphere, this is done only with a spatial resolution sufficient to resolve the gradients of the problem at hand—about 100 km in the present study. The particles are initiated using observations from DE-1 and POLAR to guide the selection of parameters. The code can be run in either guiding center or full equation of motion modes, or can be switched between these modes as appropriate to the local field scales at the particle instantaneous location, using a random gyrophase selection at transitions to full equation of motion, which introduces some diffusion of the particles. For this work we ran the code locked in full equation of motion mode, to assure reproducibility of the trajectories, without any artificial randomization.

We investigated this matter as follows. We began with a relatively typical example of the trajectory of an out-flowing polar wind proton, following it into the neutral sheet and back toward the Earth to the plasma sheet proper. We then stopped the particle, reversed its motion in time, and backtracked it through the same calculation algorithm for the full equations of motion. After some adjustment of the calculation space and time steps to assure accurate resolution, our code proved capable of backtracking this type of trajectory back to the ionosphere, confirming the expected reversibility.

Results

Figure 1 illustrates an example of a polar wind trajectory, its passage tailward through the lobe region, entrapment in the neutral sheet, and convection back toward the Earth, where it is terminated at 30 Re. Noteworthy features of the trajectory in the figure include the large non-adiabatic energy gain when the particle crosses the neutral sheet, and the accompanying changes in pitch angle. Figure 1 also shows the return path of the same particle backward in time, showing an impressively accurate retracing of the forward trajectory. The slight differences between the forward and backward legs can be attributed to numerical errors in the extensive integration of this trajectory through many gyro periods and highly structured fields. For these integrations the calculation time step was set at 0.025 gyro-period, while the spatial update interval for revising the electric field was set at 100 km, that is, small enough to resolve the neutral sheet curvature.

Not surprisingly in retrospect, we found that the reverse trajectory diverged from the forward trajectory for even the slightest modifications of the particle conditions at the termination point. An example of the full forward and reverse trajectories is shown in **Figure 2**, in which the gyrophase of the particle was changed by 0.2° before reversing its direction. The trajectory was stopped where the local pitch angle reached 90°, signifying a mirror point, and indicating that the particle on this trajectory could no longer have come from the ionosphere, but would have to have been injected from higher altitudes in the cusp region to enter the reverse trajectory.

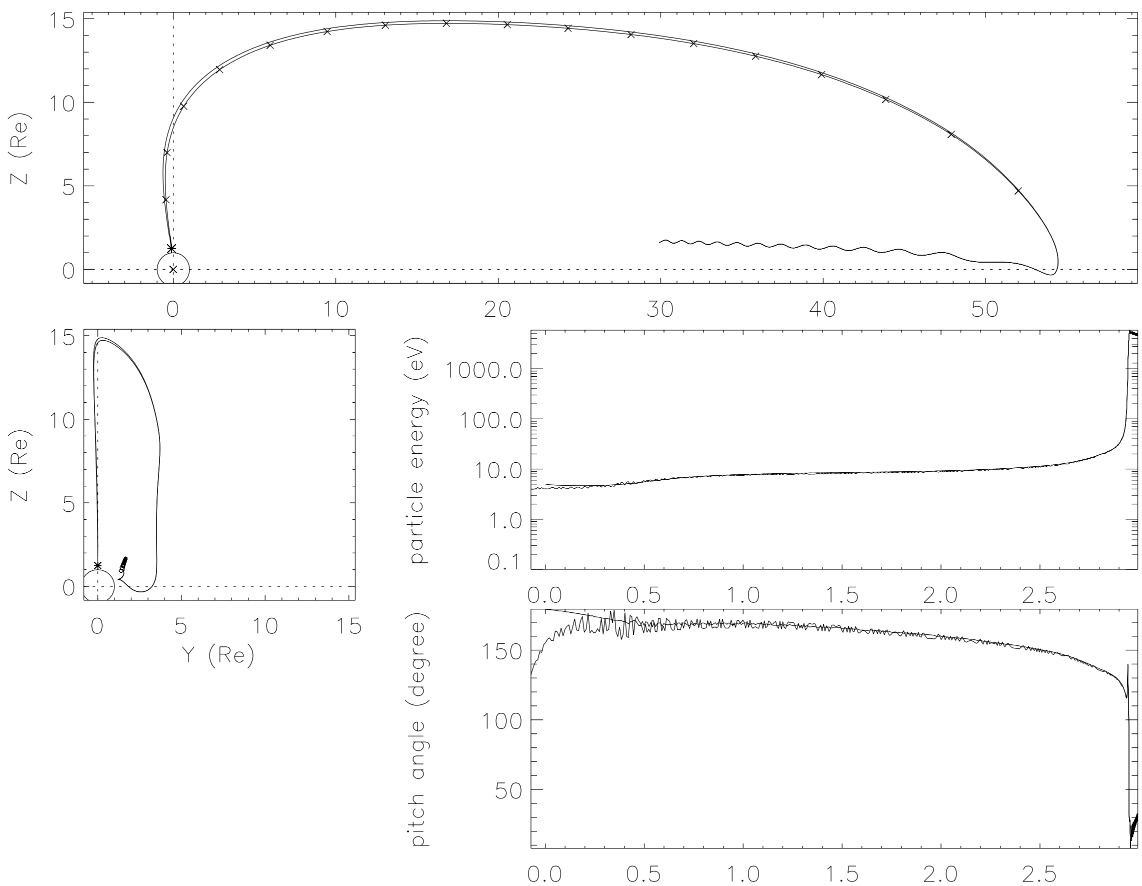

Figure 1. An example of a polar wind trajectory originating in the polar cap and entering the plasma sheet, and the reverse calculation of the same trajectory, retracing it fairly accurately.

The implication of this result is that the ionospheric source appears in the plasma sheet as an extremely localized feature(s) in velocity space. This immediately explains why a plasma sheet particle with a randomly chosen velocity would have a very small probability of backtracking to the ionosphere, as we and others have found. To further pursue this hypothesis, we systematically explored the velocity space around the chosen polar wind trajectory, using thousands of runs of the trajectory code to determine the outcomes of selected changes of velocity. The ionospheric source feature was so narrow, yet extended, that this had to be done interactively, planning each set of runs based on the previous slice through the groove feature.

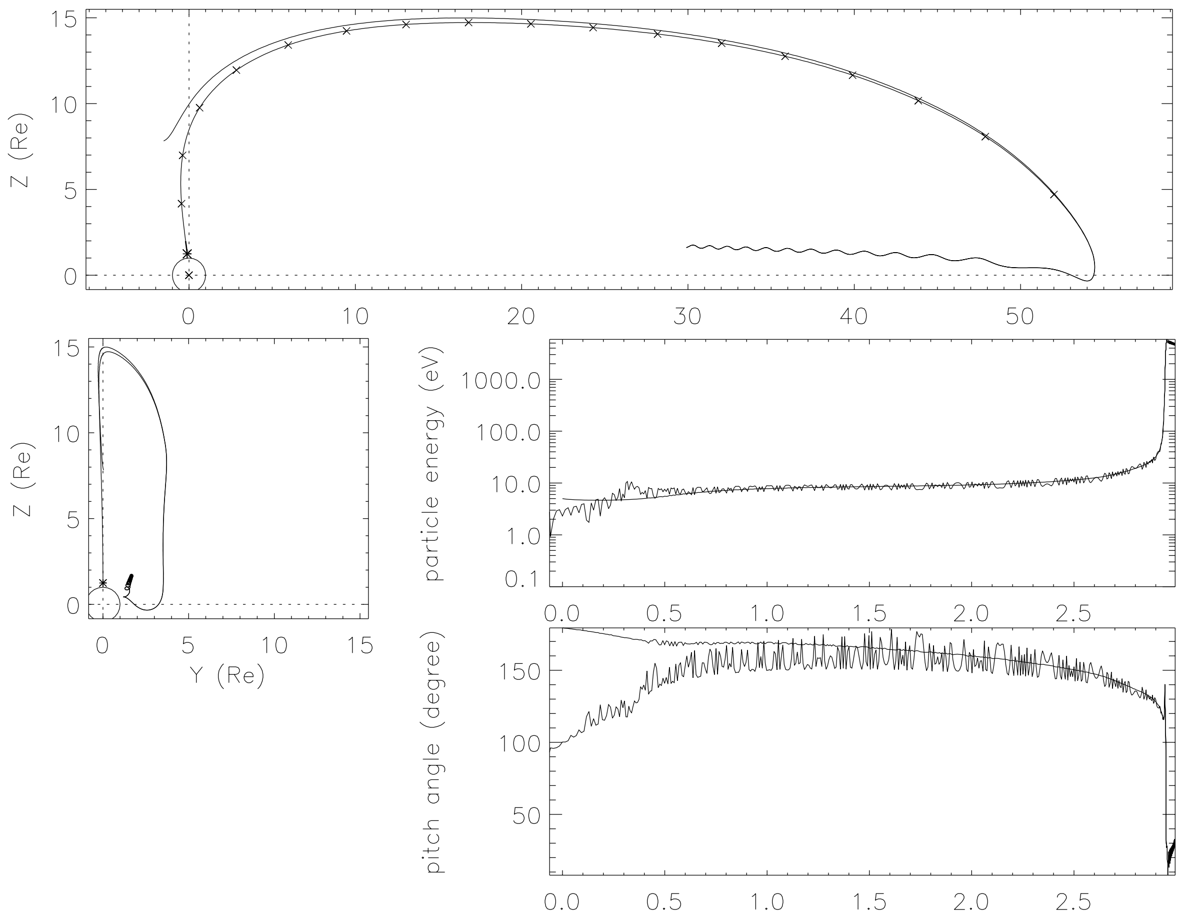

Figure 2. The effect of varying the gyrophase of the particle by 0.2° from the value with which it arrived at the termination point, before reversing the calculation, illustrating the divergence from the forward trajectory that results.

The results are summarized in **Figure 3**, where the mirror height of the reverse trajectory is contour-plotted as a function of change in velocity components at the termination point, prior to backtracking the trajectory.

Varying the pitch angle of the particle around the value with which it arrived at the termination point has a similar effect on the outcome; that is, a small change in pitch angle causes the trajectory to fail to return to so low a point in the topside ionosphere. The source region rises by an Earth radius for a pitch angle change of only a fraction of a degree.

Varying the energy of the particle around the value with which it arrived at the termination point also strongly affects the outcome. The source region rises an Earth radius for an energy change of only 0.1 %.

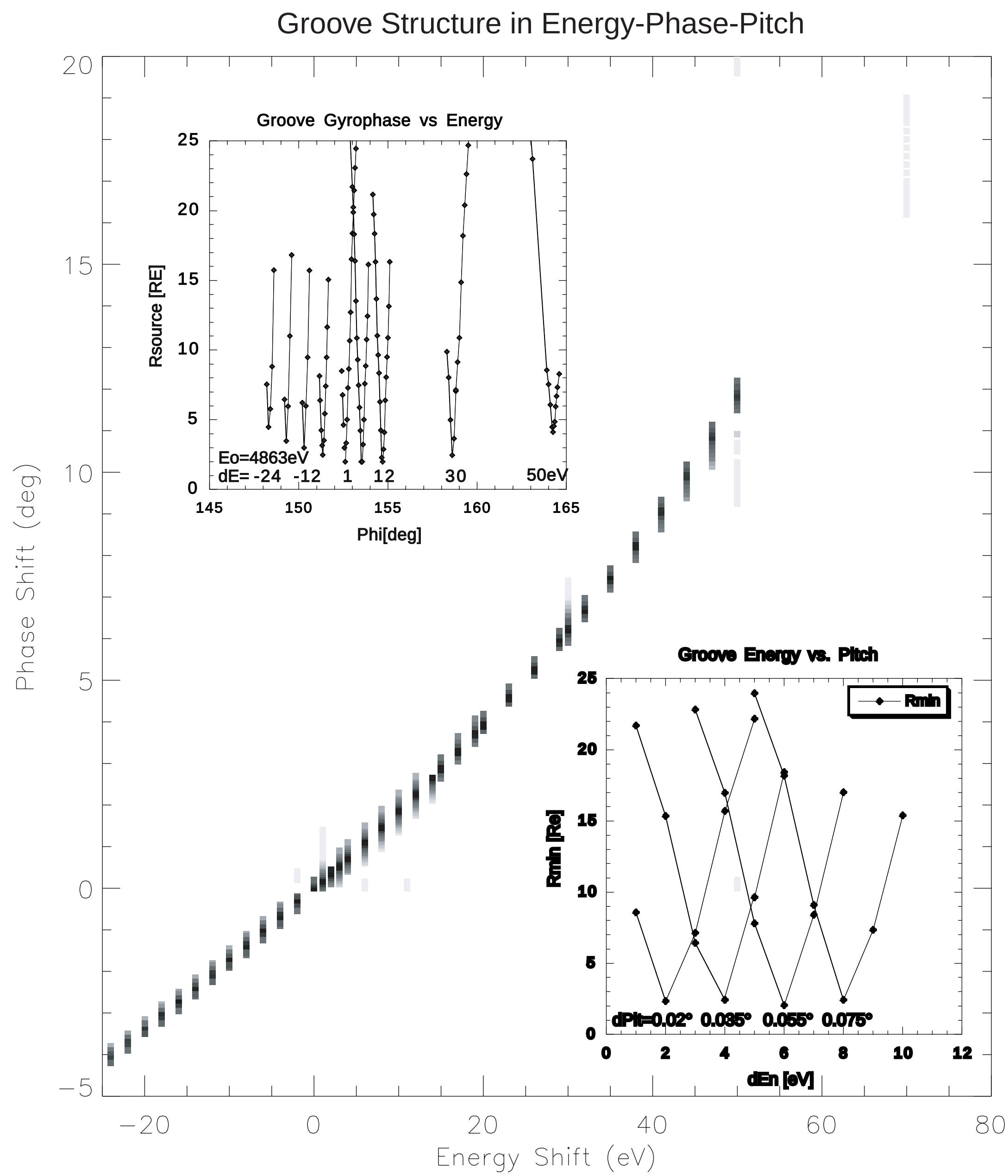

Figure 3. The three-dimensional region of velocity space that maps back to the ionospheric source for the class of particle in Figures 1 and 2 (~ 5 keV at termination point). The z-axis is contoured with black ~ 2 RE ≤ mirror radius ≤ 20 RE ~ white.

The resulting region is narrow in any single velocity parameter dimension, but the dimensions are coupled such that the feature is elongated in velocity space. As the shape of the feature was exposed by our trajectory runs, we adopted the term “groove” to describe it. Inset into the figure are smaller figures showing the cross sectional variations of the source height for various dimensions, which strengthen the rationale for this nomenclature.

It can be seen that the various components of velocity can be traded against each other so as to define an extended yet extremely thin feature we have come to refer to as the “plasma sheet source groove”. In this “groove”, the mirror height of the trajectory is low enough to be connected to the topside ionosphere, whereas the mirror height rises rapidly as velocity differs from that within the groove. The groove is sloped in velocity space across the magnetic coordinates that usually organize plasma distribution features. When populated with ionospheric phase space densities, such a feature would be highly angyrotropic, and could certainly be characterized as a gyro-phase bunched distribution.

Discussion and Interpretation

We have used three dimensional particle trajectory calculations to investigate the distribution of ionospheric source ions within the velocity space of the central plasma sheet. In contrast with earlier studies that have sought to trace particle origins backward from the plasma sheet to their sources, we have first identified ionospheric source points by running trajectories forward in time from a known source region. Having identified the velocity of the source region at the termination point, we explored its extent and shape in velocity space by running trajectories backward from nearby regions of phase space. We found the source region to be so small in cross-section as to merit the term source “groove”, bearing no resemblance to the familiar source-loss cones of the inner, more dipolar, and more slowly convecting magnetosphere.

Tracing backward in time to the ionosphere is equivalent to particle injection inside the loss cone in forward calculations. It has been shown in previous studies that such an injection is extremely difficult to achieve in the distant tail both because the loss cone is made very small (extremely large B ratio between tail and ionosphere) and because the magnetic moment damping at the origin of such injections only occurs at specific phases of gyration.

The source groove shape is locally similar to a section of an inclined screw akin to Leonardo da Vinci's airscrew helicopter. This can be understood as follows: The sensitivity to velocity originates mainly from the part of the trajectory that lies near the neutral sheet crossing, which in turn lies somewhat upstream (along the trajectory) of the plasma sheet point in question, in the case studied, about a dozen gyro-periods. The trajectory that returns to the ionosphere is unique in the specific gyrophase with which it rounds the corner of the neutral sheet crossing. A change in one component of the terminal particle velocity (e.g. its gyrophase) can be compensated by a compensating change in another component of its velocity (e.g. parallel speed), such that a constant gyrophase is maintained near the neutral sheet crossing. A change in pitch angle can similarly be compensated by changes in parallel speed or gyrophase. Considering this view of the creation of the groove, it can be hypothesized that this is in some sense a spatial gyro-resonance effect that may lead to the existence of multiple groove features in velocity space. However, we have not been able to confirm this hypothesis to date.

This study resolves the apparent paradox of the divergent behavior of trajectories run forward from the ionospheric source to the plasma sheet, compared with those run backward in time from the plasma sheet. It further crystallizes the rather severe problem of tracing plasmas via chaotic transport to their sources. The central plasma sheet is shown to be a mixture of particles that have come from the ionosphere through the lobes of the magnetosphere and other particles that have come sunward from down the tail through the lobes, both ultimately being convected into the near-Earth plasma sheet from the lobes.

At first glance this result seems compatible with a relatively minor contribution to the plasma sheet from the ionosphere. However, in the study of Fok et al. [1998], it was found that particles of the latter type made a negligible contribution to the plasma in the central plasma sheet, for the simple reason that the plasmas that exist within the distant lobes are mainly of mantle origin and are hypersonically streaming anti-sunward. The amount of phase space density in such a distribution, having a velocity compatible with the trajectories that backtrack there from the plasma sheet (i.e. Sunward), is exceedingly small unless a hot halo or reflected population exists. The key to solar wind entry into the plasma sheet, according to this analysis, must lie in the production of hot isotropic or reflected components in the solar wind at such locations in the tail.

On the other hand, substantial phase space densities are contained in ionospheric outflows through the lobe. In fact, the lobe is entirely dominated by such outflows, almost by definition, but also in observational fact. Exceptions prove the rule, of course, and there are many exceptions involving cross polar cap auroral arcs and other types of energetic plasmas in the polar cap. But the typical polar cap plasma is almost solely of ionospheric origin, essentially all of these particles destined to enter the plasma sheet after being energized by chaotic neutral sheet motions.

Thus, the mean fields of the plasma sheet would produce a plasma whose velocity space consists of a sparse set of high-PSD ionospheric source "grooves", separated by large volumes of relatively empty phase space (unless superthermal solar particles are generated in the distant tail, tending to populate the large volumes of "interstitial" phase space with corresponding fluxes). Such a velocity distribution should be expected to produce strong plasma waves at wavelengths and in modes that will be effective in smoothing the velocity distributions. Fluctuations of the real fields in the plasma sheet are well-known to exist, and may originate to some degree from the requirement to smooth the high-PSD peaks throughout the balance of phase space, and to reduce the structure that would otherwise be created by the mean or steady fields.

Conclusions

To understand an apparent paradox involving the motion of particles in idealized magnetotail fields, we used three-dimensional non-adiabatic trajectory calculations for particles typical of the high altitude polar wind. We found that the ionospheric “source cone” within the plasma sheet is formed by chaotic neutral sheet motions into a tightly localized source region that occupies a tiny fraction of velocity space, with a shape that evokes the term “source groove.” Analogous to the production of counter-streaming beams in a flux tube with symmetric source cones, multiple intense source “grooves”, spread throughout an otherwise relatively vacant velocity space, imply the growth of waves, producing diffusion and violating the initial assumption of steady and continuous fields. This "spotty" structure of velocity space is a direct consequence of the chaotic nature of ion motion in the magnetotail. That is, it originates from this chaos, and may have implications that we have only glimpsed at present.

We have explored the nature of reversible single-particle trajectories in the typical mean fields of the polar cap, lobes, and plasma sheet. We found that an analogue of the more familiar source-loss cone exists in the plasma sheet, but in the form of a sharply localized “source groove” in velocity space. Such source grooves have extents in pitch and gyrophase of less than 1 deg. and energy extent less than 0.01%. This extreme localization of ionospheric outflow trajectories into tiny grooves of velocity space resolves the apparent paradox between forward and backward-reversible trajectories terminating in the plasma sheet. It also implies that fluctuations will be produced in the plasma sheet, appropriate to diffuse ionospheric fluxes out of the source “grooves”, thereby filling up what would otherwise be a relatively vacant velocity space, on central plasma sheet flux tubes containing little or no solar plasma.

This study leads to the conclusion that test particle backtracking from or through highly chaotic regions is impractical and should be supported by forward modeling of plasma flows up to the boundaries of such regions, along the lines of the multi-fluid MHD simulation of Winglee [1998]. The implication of this study, which needs more work to substantiate, is that the ionosphere may not only supply the bulk of the plasma in the central plasma sheet, earthward of the neutral line, when high latitude convection exists, but may also be responsible for a spectrum of plasma waves that is required to smooth out what would otherwise be an over-structured plasma velocity distribution.

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